Advanced HPC Multiphysics Modeling of Motors and Materials

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Overview

Timeline

- **Start – FY18**
- **End – FY20**
- **17% complete**

Barriers

- **Power Density**: Achieving 50 kW/L will require understanding and quantifying the physics of materials and their interactions under extreme power and temperature
- **Reliability:** Reaching 300,000 mile lifetime will require understanding non-ideal material behaviors to predict and mitigate failure modes due to – for example – higher bus voltages and higher temperature operation
- **Cost:** Reducing cost to $3.3/kW will require high fidelity virtual prototyping of new motor designs to minimize expensive materials while meeting power density and reliability targets

Budget

- **Total project funding**
  - **DOE share – 100%**
- **Funding received in FY17: NA**
- **Funding for FY18: $648K**

Partners

- **Ames Laboratory**
- **National Renewable Energy Laboratory**
- **ORNL team members:** Jason Pries, Tim Burress, Tsarafidy Raminosoa, and Randy Wiles

Any proposed future work is subject to change based on funding levels

Project Objective and Relevance

- **Overall Objective:** Develop high-fidelity, high-performance computing (HPC) tools for electric motor design, optimization, and virtual prototyping
  - Support knowledge discovery and innovations in electric motor designs by increasing optimization throughput by developing open-source, high-performance computing tools
  - Develop new and improved material models to better predict electric motor behavior due to complex multi-physical interactions
  - Use high-performance computing to address reliability concerns due to non-ideal component behavior including
    - Switching voltage transients
    - Localized heating and demagnetization
    - Reduced rare-earth magnets
- **FY18 Objective:**
  - Validate baseline 2D motor simulation tool
  - Develop optimization algorithms for ORNL's HPC resources
  - Research permanent magnet hysteresis models to predict permanent magnet losses and demagnetization characteristics to aide non-rare earth permanent magnet motor design
  - Release beta version of **OeRSTED:** Oak Ridge Simulation Toolkit for Electromagnetic Devices, an open source software project

Milestones

Date	Milestones and Go/No-Go Decisions	Status
December 2017	Milestone: Design and implement a parameterized motor model for parallelization scaling studies	Complete
March 2018	Milestone: Scale motor optimization algorithms to operate on multi-node HPC systems	Complete
June 2018	Go/No-Go decision: Determine if permanent magnet hysteresis can be modeled using previously developed techniques for soft magnetic materials	On Track
September 2018	Milestone: Validate the proof of concept high fidelity finite element analysis motor simulator with integrated magnetic hysteresis characteristics	On Track

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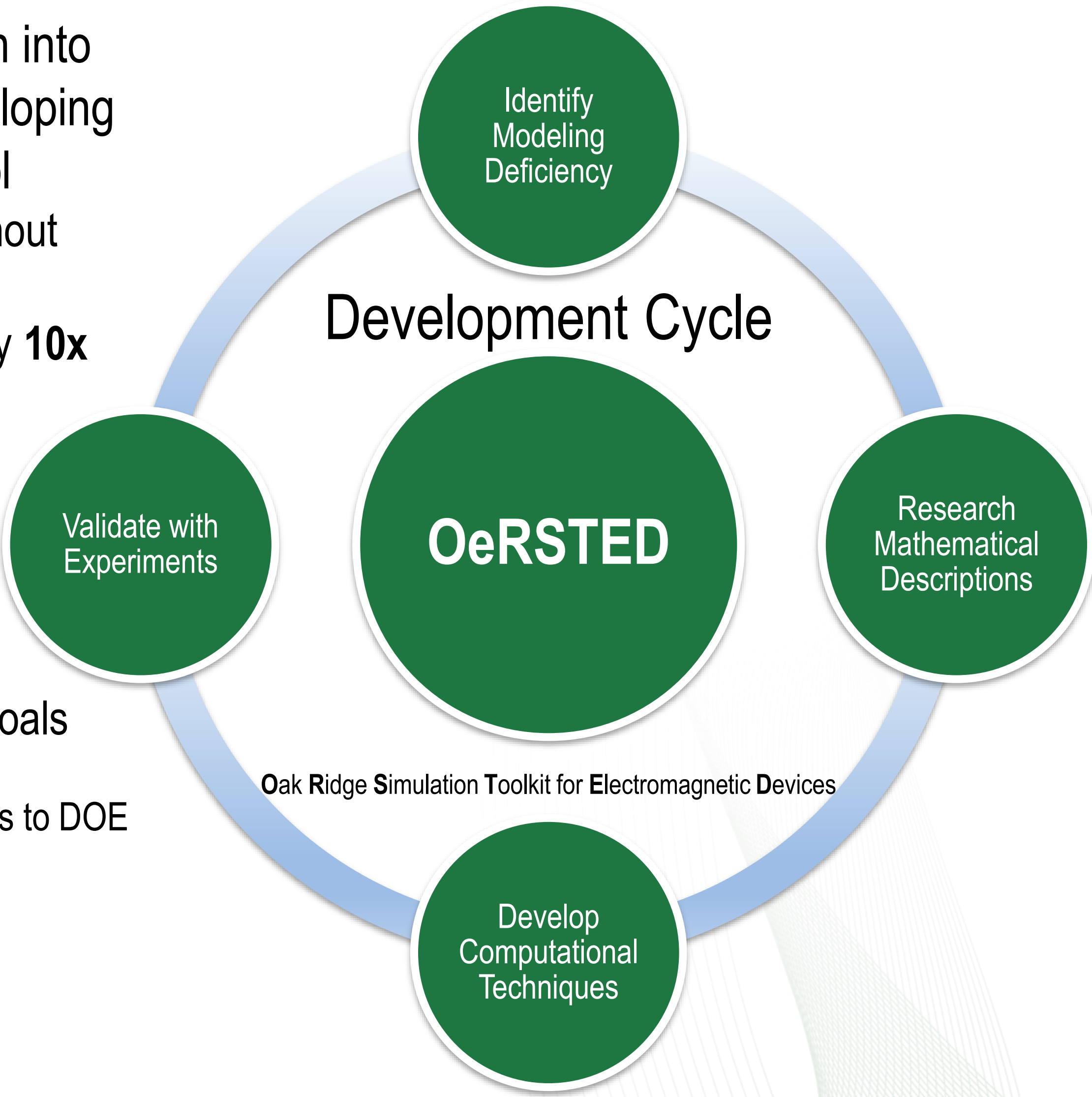
Approach/Strategy

- **Goal:** Support early stage research into high power density motors by developing a high fidelity HPC optimization tool
  - Reduce modeling error to **<5%** without heuristic ‘corrections’
  - Increase optimization throughput by **10x**

- **Impact and Uniqueness:**
  - Focus on multiphysics interactions
    - Phenomena previously considered too complex, computationally intensive
    - New and existing materials
  - Tool for pursuit of DOE ELT 2025 goals
    - Open source software
    - Facilitate industry and academia access to DOE HPC resources



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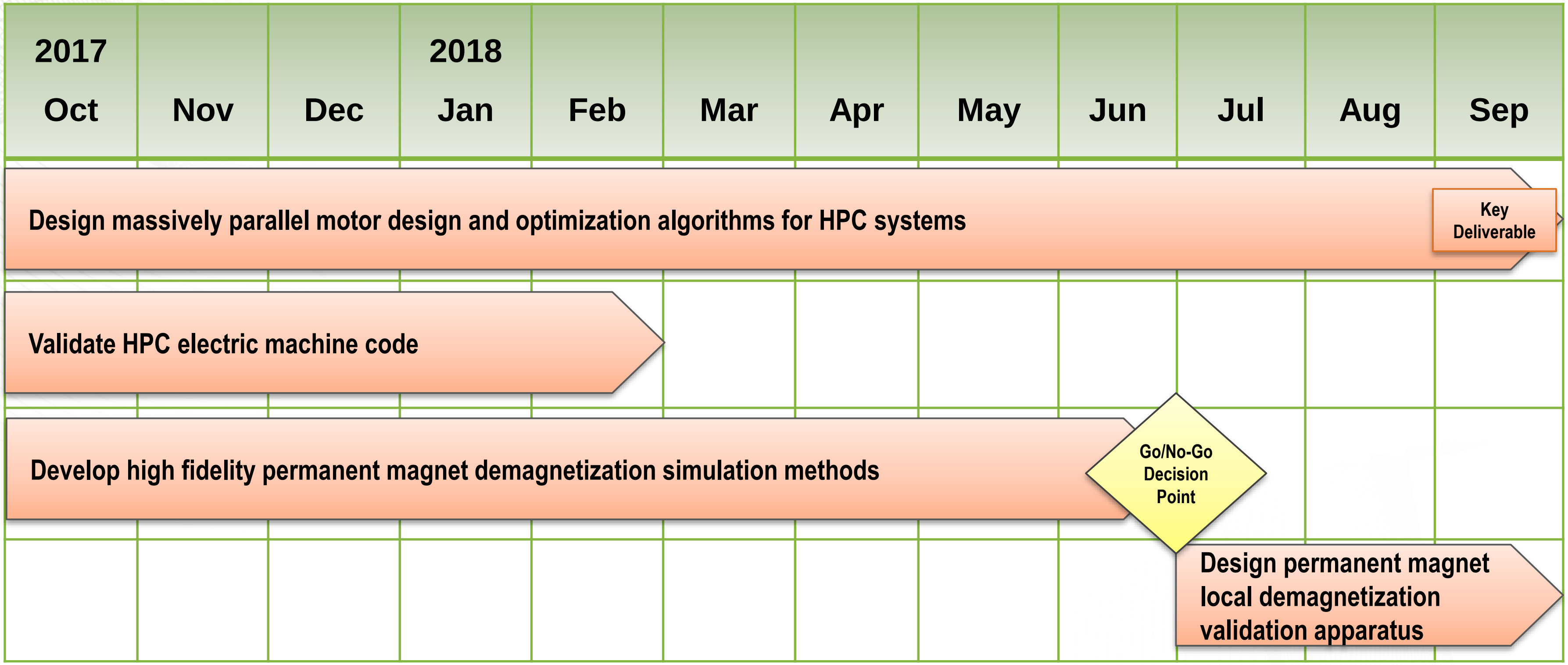
Approach FY18 Timeline



Go/No-Go Decision Point: Determine if permanent magnet hysteresis can be modeled using previously developed techniques for soft magnetic materials

Key Deliverable: Beta release of open-source software OeRSTED, the Oak Ridge Simulation Toolkit for Electromagnetic Devices

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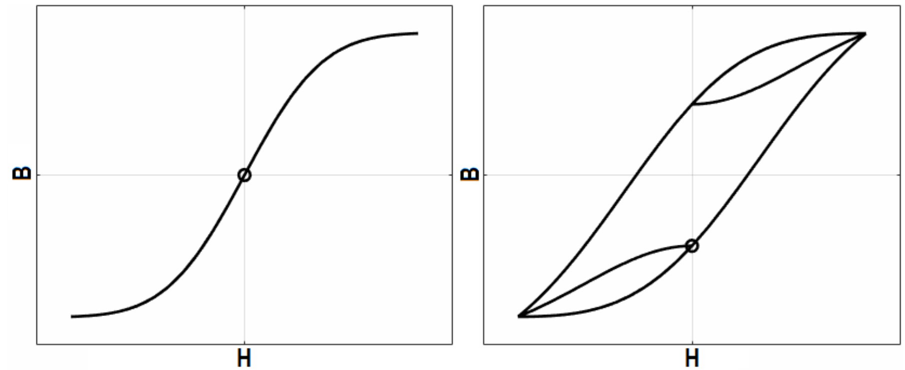
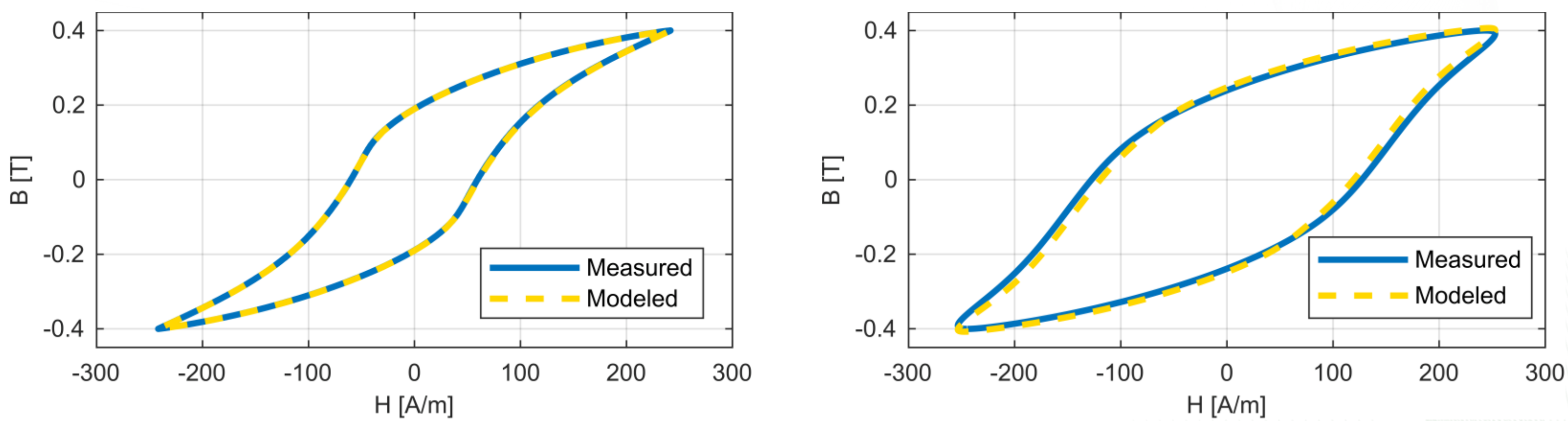
Technical Accomplishments - FY17

Developed 1D Soft Magnetic Hysteresis and Dynamic Loss Model

- **Goal:** Improve motor modeling fidelity
- **Challenge:** Standard magnetic models utilize lossless, scalar B-H field constitutive relationships. Real magnetic materials are lossy, exhibiting hysteretic behavior with losses increasing with frequency
- **Solution:** Integrate a detailed magnetic hysteresis model into a dynamic finite-element eddy current solver



Standard magnetic material model is scalar and losses (left) while the improved model captures losses due to both major and minor hysteresis loops (right)



Simulated and experimentally measured B-H loops at 5Hz (right) and 500Hz left showing loop widening and increased losses with frequency

- **Impact:** Fundamental change in dynamic loss modeling in simple magnetic structures

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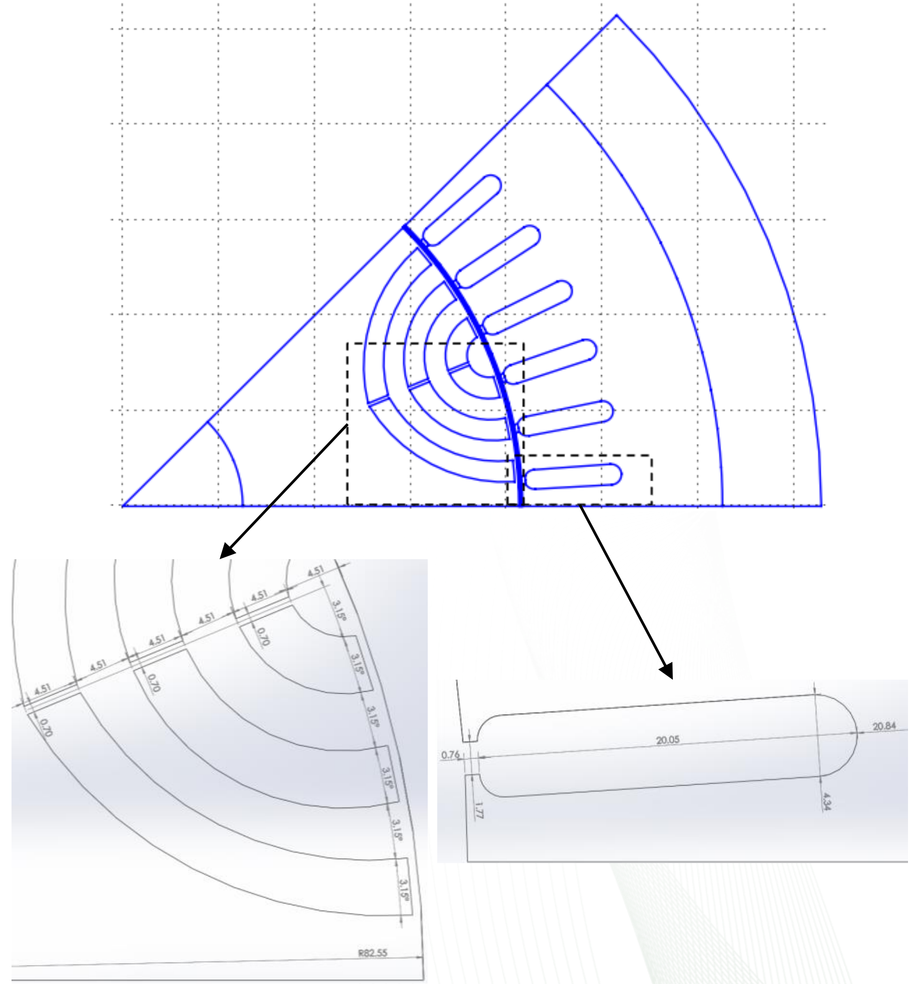
Technical Accomplishments - FY18

Developed a Nonlinear Geometric Constraint Solver

- **Goal:** Enable motor optimization on HPC systems to support knowledge discovery
- **Barriers:**
  - Optimization requires geometrically parameterized models for numerical analysis
  - HPC systems require compiling code on unique Linux operating system, limiting the use of commercial software
  - No open-source software exists for describing nonlinear geometric modeling constraints used in typical design workflows
- **Solution:** Develop a modular, reusable nonlinear geometric constraint solver to drive HPC motor optimization code
- **Impact:** Geometric constraint solver facilities HPC motor optimization and will make utilization of the code easy for future partners

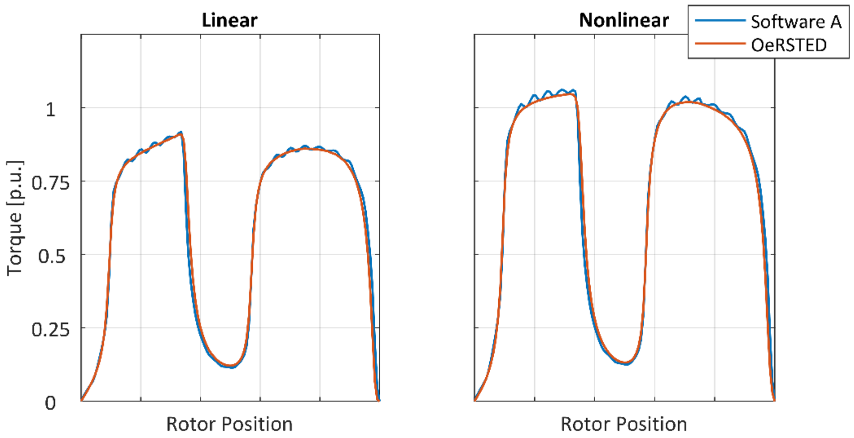


Top: *21 parameter model of a synchronous reluctance machine constructed using OeRSTED's nonlinear geometric constraint solver*
Bottom: *Detailed view of the rotor (left) and stator (right) parameters from the same model constructed using SOLIDWORKS*

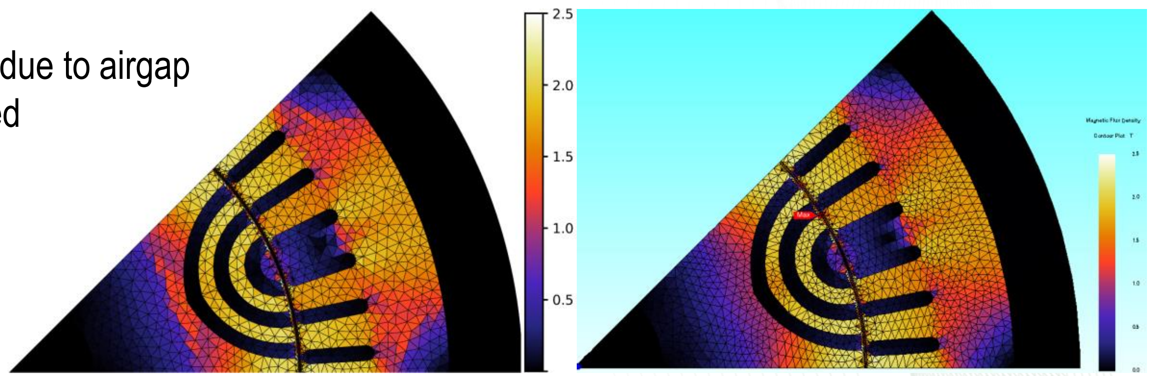
Technical Accomplishments - FY18

Validated 2D Magnetostatic Solver

- **Goal:** Improve motor modeling fidelity and facilitate optimization on HPC systems
- **Challenge:** A baseline for measuring future accuracy improvements must be established
- **Solution:** Implement identical motor models in different software packages and verify results are identical to within discretization error
- **Impact:**
  - Validated parity with state-of-the-art commercially available software in terms computational speed and accuracy
  - Eliminated non-physical oscillations due to airgap discretization error using an improved computational technique



Simulated locked rotor torque of a salient pole synchronous machines using a linear magnetic material property (left) and non-linear material property (right)

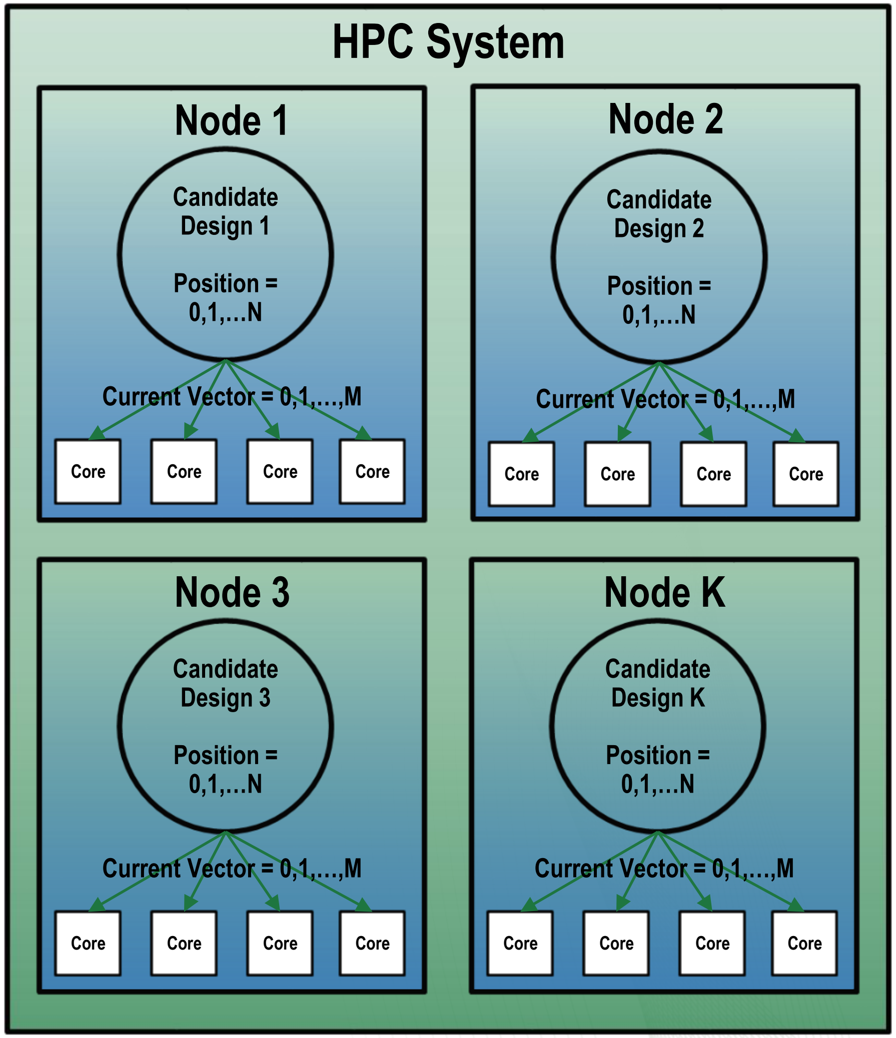


Magnetic flux density plot of a synchronous reluctance motor simulated using OeRSTED (left) and commercially available software (right)

Technical Accomplishments - FY18

Developed HPC Motor Efficiency Map Identification Routine

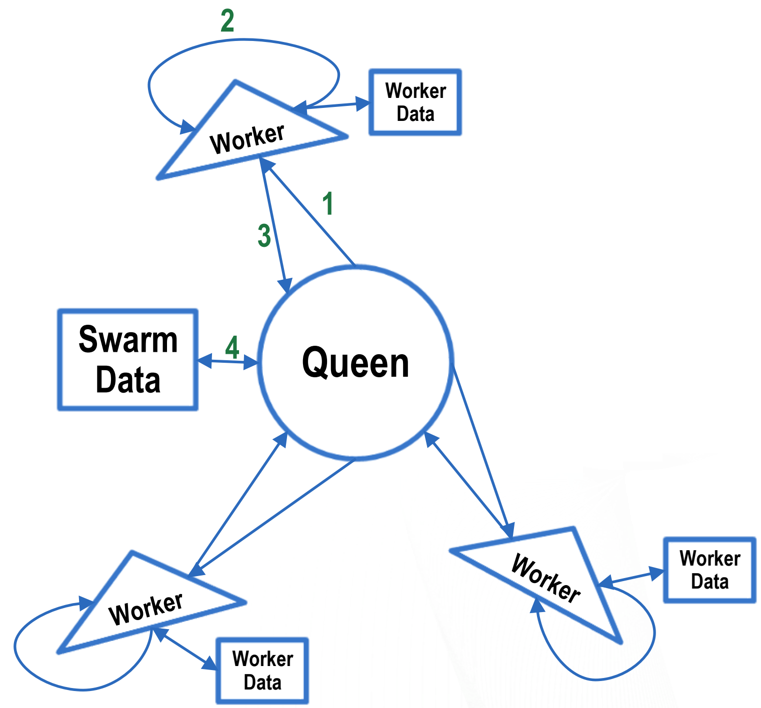
- **Goal:** Enable motor optimization on HPC systems to support knowledge discovery
- **Challenges:**
  - Robust motor optimization requires identification of the entire efficiency map for each candidate
  - Achieving maximal HPC throughput requires careful consideration of usage of computational and memory resources at every level
- **Solution:** Perform computational experiments to determine best work distribution strategy for motor optimization
- **Impact:**
  - Achieved near linear scaling of individual design efficiency map identification up to number of cores per node (30x speedup versus single core)
  - Achieved linear scaling of multiple design analysis/optimization up to number of nodes requested (40)



Work distribution for massively parallelized motor optimization

Technical Accomplishments - FY18
Developed an Asynchronous Particle Swarm Optimization Algorithm

- **Goal:** Enable motor optimization on HPC systems to support knowledge discovery
- **Challenges:**
  - Standard particle swarm optimization requires synchronization of all particles
  - Differences in model size and magnetic saturation level cause variations in simulation time
  - Synchronization requirements means optimization speed is limited by longest evaluation time
- **Solution:** Design an asynchronous particle swarm optimization algorithm using a hub/spoke topology with delayed information sharing
- **Impact:** Developed a faster, more robust optimization algorithm and validated that information delays have negligible impact on behavior of PSO algorithm



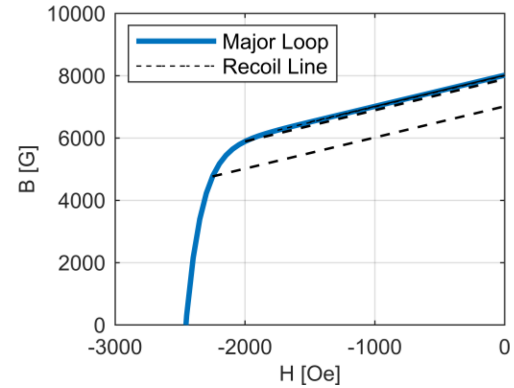
Asynchronous fully-informed particle swarm topology

1. *Queen sends task to worker*
2. *Worker performs computation*
3. *Worker sends data to Queen*
4. *Queen updates swarm status*

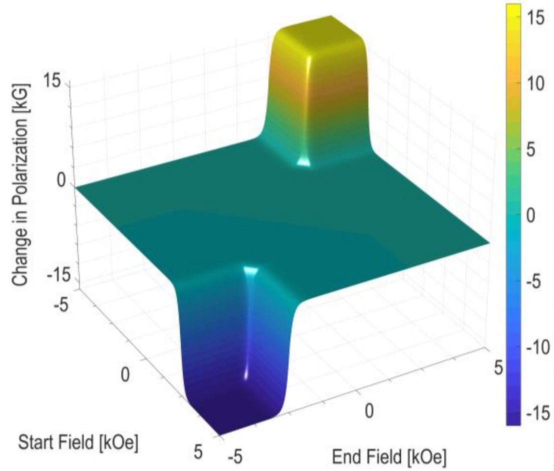
Technical Accomplishments - FY18

Analyzed PM Demagnetization and Recoil Models

- **Goal:** Support the development of non-rare earth magnet electric motors by improve permanent magnet modeling fidelity
- **Challenge:** Low coercivity of reduced and rare-earth free PMs result in reliability concerns due to demagnetization
- **Solution:** Explore using soft magnetic material model approach to accurately capture PM demagnetization and loss characteristics
- **Impact**
  - Validated assumption that similar methods can be used to model both hard and soft magnet material characteristics
  - Based on previous work, substantial accuracy improvements are expected



Modeled permanent magnet second-quadrant behavior showing lossy recoil characteristics (Collaboration with Ames Laboratory)



Two-dimensional polarization plot estimating the four-quadrant behavior of a permanent magnet from limited data

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Responses to Previous Year Reviewers' Comments

This project is a new start

Collaboration and Coordination with Other Institutions

AMES LABORATORY Creating Materials & Energy Solutions U.S. DEPARTMENT OF ENERGY	**Ames Laboratory** • Gave talks at the Critical Materials Institute and at the DREaM workshop • Investigating the use of HPC to analyze motor designs using newly developed non-rare earth permanent magnet material • Leveraging existing experimental work performed by Ames to validate permanent magnet demagnetization and loss modeling techniques
NREL NATIONAL RENEWABLE ENERGY LABORATORY	**National Renewable Energy Laboratory** • Considering methods for integrating electric motor thermal management research results into future HPC work on thermal simulations and temperature dependent magnetics

Remaining Challenges and Barriers for FY18

- Numerical analysis and filtering of noisy experimental data must be performed in order to identify appropriate parameters for the permanent magnet computational models
- The spatial distribution of the magnetic field of a permanent magnet must be measured to validate the accuracy of local demagnetization simulations

Any proposed future work is subject to change based on funding levels

Proposed Future Work

- **Remainder of FY18**
  – Complete development proof-of-principle permanent magnet demagnetization modeling and simulation tool
  – Validate permanent magnet simulations against four-quadrant magnetization data

- **FY19**
  – Experimentally validate results from local demagnetization simulations
  – Investigate vector hysteresis models for capturing rotational core losses in electrical steel to improve motor core loss simulation accuracy
  – Develop methods to utilize accelerators/GPGPUs (general purpose graphical processing units) to increase computational speed

Any proposed future work is subject to change based on funding levels

Summary

- **Relevance:** Increased motor modeling fidelity and optimization throughput will accelerate improvements in electric motor designs to achieve the 2025 DOE ELT targets of 50kW/L, $6/kW, and 300,000 mile lifetime
- **Approach:** Research sources of modeling discrepancies, develop new numerical methods, and implement motor optimization tools on DOE HPC systems
- **Collaborations:**
  - **Ames:** Leveraging existing work on developing AlNiCo magnets to improve material models for motor design and optimization
  - **NREL:** Exploring best methods to integrate data from thermal management research into future work on HPC thermal modeling
- **Technical Accomplishments:**
  - Developed a dynamic loss modeling method for soft magnetic materials
  - Implemented a nonlinear geometric constraint solver to support motor optimization
  - Validated core code base against existing commercial FEA software
  - Researched optimal work allocations to fully utilize HPC resources for motor design
  - Designed a new asynchronous particle swarm optimization algorithm
  - Validated assumption on unified soft/hard magnetic material modeling method
- **Future Work:**
  - Validate local demagnetization simulations
  - Research computationally efficient vector hysteresis models to improve core loss accuracy
  - Develop GPGPU simulation algorithms to improve simulation speed

Any proposed future work is subject to change based on funding levels